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Natural Hazards, Fish Habitat, and Fishing Communities in Alaska

Christian E. Zimmerman*, Christina A. Neal, and Peter J. Haeussler
U.S. Geological Survey, Alaska Science Center
4230 University Drive, Suite 201, Anchorage, Alaska 99508, USA

Abstract.—Fish and fishing communities are iconic symbols of Alaska. Volcanoes, earthquakes, and tsunamis also stand out as processes that define or shape the Alaska landscape. Alaska has numerous fishing ports that regularly rank in the top 10 ports for commercial landings by weight and value in the United States. In addition to commercial fisheries, subsistence fisheries and sport fishing play an important role in the economy and culture of Alaska. Alaska is home to one of the most active plate boundaries on the planet, where the Pacific Plate is subducting the North American Plate at rates greater than 5 cm/year. This process brings to Alaska earthquakes, tsunamis, and volcanic eruptions. Active plate boundaries around the Pacific basin also make Alaska vulnerable to transoceanic tsunamis generated by earthquakes thousands of miles away. Alaska is the most seismically active state in the United States by a large margin and one of the most active areas in the world. In this paper, we examine the distribution of fishing communities and fish habitat with respect to volcanic and earthquake hazards and discuss the possible implications of these natural hazards to fisheries. Because natural hazards cannot be prevented, communities must prepare for and minimize risk associated with such events. Understanding the nature and distribution of natural hazards is the first step in preparing for future events and limiting the impacts of those events.

Introduction

Fish and fishing communities are central icons of Alaska and play an important role in the social and economic status of the state. Commercial, subsistence, and sport fisheries are important sources of income and food for communities throughout the state. For example, in 2005, commercial fishermen were paid nearly $1.3 billion for salmon, halibut, shellfish, groundfish, and herring harvested in Alaskan waters (ADFG 2006). Sport fishing is estimated to be worth more than $500 million annually (ADFG 2003). Similarly, subsistence fisheries, which are defined as fisheries for noncommercial, customary, and traditional uses, not only provide food and other necessities, but are a way of life. Subsistence fisheries are of such importance to communities that state and federal laws provide both protection for this type of fishery and give it priority over other uses of fish resources (Wolfe 1998).

According to the Alaska Fish Distribution Database maintained by the Alaska Department of Fish and Game, the state contains more than 16,000 bodies of water, including streams, rivers, and lakes that are used by anadromous fishes such as salmon, char, and whitefish for spawning, rearing, or migration (Figure 1; Johnson and Weiss 2006). Coastal waters of the North Pacific Ocean, Bering Sea, and Arctic Ocean provide habitat important to many commercial fisheries.

Other iconic features of the Alaskan landscape include natural hazards such as volcanoes and earthquakes. In this paper, we describe the distribution of these hazards relative to fishing communities and fish habitat. While other natural hazards, such as wildfire, exist in Alaska and have impacts at local scales, we focus our attention on regional or

* Corresponding author: czimmerman@usgs.gov

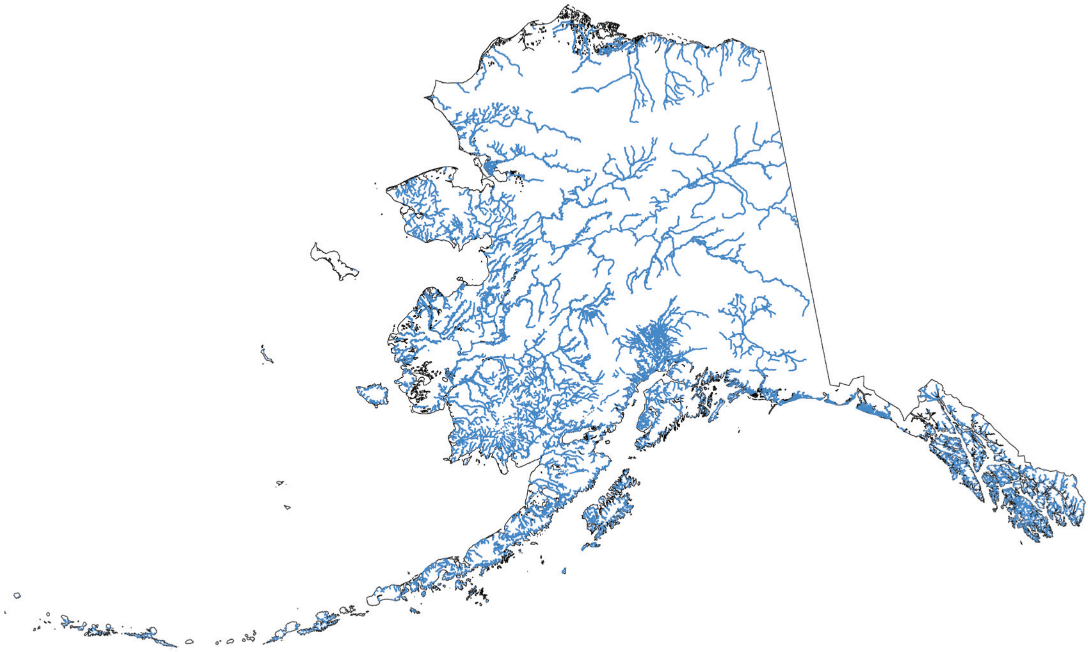

Figure 1. Distribution of stream, river, and lake habitats used by anadromous fishes in Alaska. Data from the Anadromous Waters Catalog (Johnson and Weiss 2006).

statewide hazards associated with volcanoes and earthquakes. First, we describe the nature and extent of volcanic and earthquake hazards. Then, we discuss case studies of selected events with an emphasis on their potential or realized impacts to fishery dependent communities and fish habitat.

To assess the relation of fishery-dependent communities and risk from volcanoes and earthquakes, we mapped the distribution of communities relative to volcanoes and earthquake risk. Sepez et al. (2005) used quantitative indicators to identify 136 communities considered to be dependent on involvement in commercial fisheries based on commercial fishery landings, number of processors, vessel registrations, number of crew licenses, and number of state and federal permit holders. Many more communities are also dependent upon recreational and subsistence fisheries, but limited data are available to reliably quantify dependence on these fisheries. Sport fishing-dependent lodges, guides, and communities are distributed throughout Alaska and are likely to be susceptible to hazards, but due to a lack of information concerning the distribution of sport fishing, we focus our discussion of risk to communities dependent on commercial fisheries. The communities identified by Sepez et al. (2005) are distributed throughout Alaska (Figure 2).

Volcano Hazards in Alaska

Alaska contains more than 40 historically active volcanoes that stretch 3,000 km from the Wrangell Mountains through Cook Inlet and along the Alaska Peninsula and Aleutian Islands (Miller et al. 1998). Based on the written record stretching back more than 200 years, an average of 1–2 eruptions occur each year, with most producing ash clouds, ash fall, and a variety of other products depending on the style and size of the event. Eruptions can be single pulses lasting minutes to hours or days, or they can be repetitive and chronic with numerous events occurring over months, years, and even decades. Alaska's volcanoes

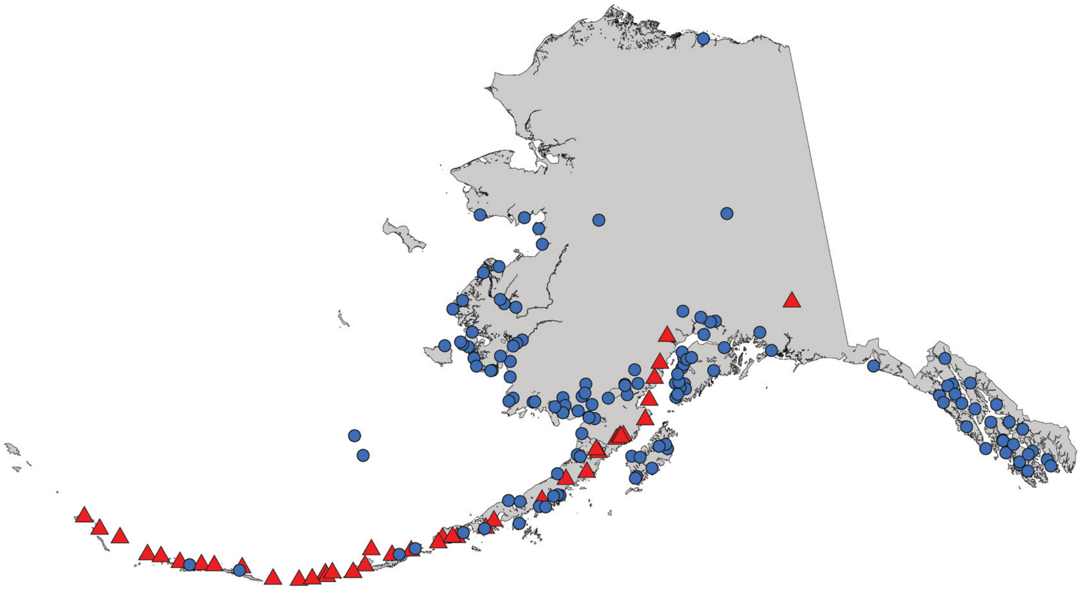

Figure 2. Distribution of fishery dependent communities (circles) and active volcanoes (triangles) in Alaska.

are typical subduction zone systems and erupt primarily andesitic lavas both explosively and effusively. Resulting processes impact areas immediately around the volcano and can affect terrain many tens or even thousands of kilometers away (Blong 1996; Myers et al. 2004). The eastern part of the volcanic arc, where oceanic crust is subducted beneath continental crust, tends to produce more silicic (and explosive) eruptions, compared to the western part of the arc, which has subduction of oceanic crust beneath another oceanic plate and where eruption of lava flows are more common. This transition occurs near the western end of Unimak Island. Fortunately, because of the sparse population in Alaska, few volcanoes in Alaska have communities or critical infrastructure immediately in harm's way.

The most common and far-reaching volcano hazard in Alaska is ash fall from ash clouds, produced during explosive fragmentation of ascending magma during volcanic eruptions of nearly all sizes and intensities. Ash—pulverized fragments of rock and volcanic glass less than 2 mm across—is ejected into the atmosphere where prevailing winds carry the ash for tens to thousands of kilometers. The largest of eruptions, such as the Novarupta eruption in 1912, can send ash around the globe. Ash clouds are a significant hazard to aircraft and can severely curtail or interrupt air travel, depending on the size and duration of the eruption. Fallout of ash, if heavy, can collapse buildings, damage vegetation, clog streams, and impact wildlife habitat for years.

Energetic eruptions can also produce ballistics, pebble- to boulder-sized fragments of rock or pumice that travel as projectiles posing a serious hazard to people and structures within several kilometers of the vent. Pyroclastic flows and surges, avalanches or hurricane-force blasts of volcanic gas, ash, and rock debris, can travel away from a vent during explosive eruptions at speeds in excess of 100 m/s. The largest of pyroclastic flows accompanying significant eruptions can bury the landscape under hundreds of meters of debris, permanently changing the landscape.

Lava flows and lava domes, products of effusive eruptions, are extremely hazardous in the immediate vicinity; sudden explosions can occur where lava comes into contact with bodies of water, snow, or ice. Occasionally, thick, silica-rich lava flows or domes can form oversteepened, unstable flow fronts that fail explosively in a sudden pyroclastic avalanche or surge.

Hot volcanic ejecta can mix with snow, ice, and surface water to form floods and lahars, destructive, fast-moving slurries of water, mud, sand, and boulders that sweep rapidly downslope and into drainages leading away from the volcano. Lahars and related flooding are common during Alaskan eruptions because of the extensive snow and ice mantle on many volcanoes. Debris avalanches, rapidly moving masses of rock, soil, and debris that form during gravitational failure of a volcano's flank, are rare but catastrophic events that can occur even without an eruption.

Volcanoes can directly affect marine or riverine environments through the production of tsunamis when volcanic debris suddenly enters a body of water; the proximity of many volcanoes to the coastline or lakes heightens this possibility in Alaska. Acidic or toxic gasses and acidic hydrothermal waters at volcanoes can be released passively or suddenly, with significant impacts on surrounding drainages or areas downwind. Finally, submarine or nearshore (littoral) volcanic eruptions can produce explosions, rafts of debris, and high-temperature, acidic zones that can negatively impact oceanic ecosystems. Long-known and recently discovered submarine volcanic vents in Alaska, such as Bogoslof Island in the Bering Sea and Amchixtam Chaxsxii in the Rat Islands, are good examples.

Of the hazardous volcanic processes discussed above, ash clouds and ash fall are the most common and far-reaching and, hence, of most concern to fishing communities and fish habitat. In the immediate vicinity of the volcano, thick accumulations of ash (centimeters or more) could bury available habitat, temporarily or for centuries. The addition of ash to water columns in lakes, rivers, and streams may have negative effects, and the degree of impact would strongly depend upon the duration of an eruption and prevailing winds. Ash fall can cause increased turbidity, which, in turn, can cause decreased productivity and decreased foraging by fish (Swenka and Hartman 2001). Further, sedimentation from ash fall is likely to affect spawning habitats with potential negative impacts due to increased fine sediment (Chapman 1988). Ash fall at sea may have temporary effects on fish; however, the strong wave and tidal action combined with ocean currents would likely clear the area rapidly. Recent experimental evidence suggests that large volume ash falls at sea could alter nutrient availability, encouraging diatoms and other phytoplankton activity with unknown impact to the oceanic food chain (Duggan et al. 2007).

Second in importance with regard to impacts to fisheries, flowage phenomena (pyroclastic flows, surges, lahars, and outburst floods), also common during typical Alaskan eruptions, can severely impact drainages and spawning fish habitat surrounding the volcano. Depending on the size of the eruption, these and other processes above can profoundly impact the landscape, ecosystems, and human infrastructure. In the largest (and rarest) of eruptions, entire watersheds, or even greater areas, may be dramatically changed by the influx of debris and shifting drainage patterns. Influx of sediment can destroy spawning streams and cut off access to migratory routes. Temporary or long-term addition of volcanic debris, high temperatures, acidic waters, or debris flows can destroy aquatic organisms and surrounding vegetation; macroinvertebrate and other food sources for fish may be eliminated or significantly perturbed, which would impose a critical stress on fish. Bisson et al. (2005) provide a case study of impacts and recovery of fish populations following the eruption of Mount St. Helens in Washington, which produced lahars and debris torrents as described above.

Examples of Alaska Eruptions and Impacts on Fisheries

Aniakchak, ~1645 BC

The 1645 BC catastrophic eruption of Aniakchak Volcano on the Alaska Peninsula (Pearce et al. 2004) is an example of the rare but ecosystem-changing type of eruption that has occurred more than a dozen times in the last 10,000 years in Alaska. During the course of an eruption that eviscerated a volcanic structure to form a 1.5-km-deep, 10-km-diameter closed crater, as much as 70 km^3 of debris was deposited in fast-moving avalanches that swept tens of kilometers in all directions, obliterating everything in their path and deeply burying streams, rivers, and lakes in the process. Undoubtedly, entire populations of salmon and other fish were instantly killed and seasonal migration and spawning routes destroyed. Eventually, the Aniakchak crater wall was breached and a new river was established between the crater and the Pacific Ocean. Analysis of genetic characteristics of modern salmon populations in the Aniakchak area indicates that volcanic activity can play an important role in the genetic structuring of populations through alteration of drainage patterns (Hamon et al. 2005).

Katmai/Novarupta, 1912

The 1912 eruption of Novarupta in what is now Katmai National Park and Preserve on the Alaska Peninsula remains the largest eruption on the planet in nearly the last two centuries (Fierstein and Hildreth 1992). Over a 60-h period, volcanic debris filled glacial valleys surrounding the vent to depths as great as 200 m. Ash, still visible today in the Katmai area, thickly blanketed the region and fell across the Gulf of Alaska, Yukon Territory, and as far away as Seattle. Fish habitat was undoubtedly destroyed or damaged for many tens of kilometers around the eruption site due to the influx of ash and coarser particles transforming the landscape into a barren wasteland. Even drainages that were able to re-establish in the years following the eruption were likely charged with excessive sediment derived from the enormous quantity of loose, unconsolidated debris that mantled slopes throughout the Katmai region. Although the eruption occurred in early June prior to the onset of a major salmon run, untold numbers of fish were likely killed during the eruption itself due to sediment loads and debris flows. Regional fisheries records indicate a decline in salmon population that persisted until the early 1920s (Dumond 1979; Fierstein 1984).

River conditions were not the only fish habitat negatively impacted by the Katmai eruption. Immediately after the cataclysmic event, in Kaflia Bay about 50 km east and directly downwind of the eruption, local residents noted floating dead fish, birds, and other animals (Schaaf 2004). Floating rafts of pumice accumulated in the Shelikof Strait and were reported in the area as many as 22 years following the eruption. While not a primary concern to ocean-traveling fish, floating pumice can interfere with vessel traffic. An eruption of this magnitude today, anywhere along the Aleutian arc, would potentially have a significant and long impact on fish populations and to any fish processing infrastructure nearby.

Redoubt, 1989–1990

Ice-covered Redoubt Volcano within Lake Clark National Park and Preserve produced a series of ash fall, lahar, and pyroclastic flow-producing events during an eruption lasting from December 1989 through June of 1990. The most significant impacts to surrounding terrain were the repeated lahars that inundated the Drift River, adding as much as 10 m of coarse volcanic sediment to the river channels and 1–5 m of sediment 40 km downstream near the mouth of the river at Cook Inlet (Dorava and Milner 1999). Such significant aggradation of sediment severely altered the course and location of primary water courses of the Drift River and perturbed adjacent drainages through channel migration and overflow. Many square kilometers of forest along the riverbanks were destroyed by lahars.

No systematic studies of the effects of these significant morphologic and hydrologic changes on aquatic life were conducted following the Redoubt eruption; however, impacts undoubtedly occurred. Dorava and Milner (1999) examined the macroinvertebrate community in the Drift River, 4 years after the 1989–1990 eruption of Redoubt, in June of 1995. According to Dorava and Milner (1999), fish access to Drift River was degraded due to sedimentation and changing channel characteristics immediately following the eruption, and anecdotal evidence suggested that diminished set-net returns of salmon in the vicinity of the mouth of the Drift River following the 1989–1990 events. Macroinvertebrate populations along the Drift River, if diminished by the eruption (this could not be shown because no baseline data existed), had recovered to levels observed in similar river settings (all glacial influenced) on the west side of Cook Inlet within 5 years (Dorava and Milner 1999.) Thus, for an eruption of the magnitude of the Redoubt event on 1989–1990, it appears that elimination of food resources for fish was not the primary limiting factor caused by the volcano. Dorava and Milner (1999) point out that, in 1995, the Drift River was still impacted by a large influx of sediment, characterized by unstable banks, and riparian vegetation had not yet recovered. If streams in the area were not glacially influenced, it is likely that macroinvertebrate communities would have been impacted to a greater degree by sediment inputs.

Chiginagak, 2004–Present

An unusual volcanic event at ice-clad Chignagak Volcano on the Alaska Peninsula illustrates a potent hazard to fish habitat around active volcanoes with acidic geothermal systems that impound water and suddenly release large volumes downstream. Sometime in late 2004 or early 2005, heat flux from within Chiginagak likely increased causing accelerated melting of snow and ice at the summit of the volcano (Schaefer et al. 2006). According to this work, in early May 2005, an estimated 3.8×10^6 m^3 of sulfurous, clay-rich debris and acidic water burst through a tunnel at the base of a glacier that mantled the south rim of a summit crater. These acidic waters flooded nearly 30 km down an unnamed drainage and into nearby Mother Goose Lake. It killed all aquatic life and prevented an important sport fishery on the King Salmon River. The flood of acidic water also killed and damaged vegetation along the flood path. Acidic conditions persisted into 2007, and the long-term impacts on local fisheries are still being evaluated (J. Schaefer, Alaska Division of Geological and Geophysical Surveys, personal communication).

The Chiginagak event of 2005 has few historical precedents worldwide but may not be an isolated event in Alaska or at Chiginagak. Ongoing studies by the U.S. Geological Survey (USGS), in conjunction with Northern Arizona University, are attempting to demonstrate whether or not past summit crater lake outbursts have impacted the Mother Goose Lake drainage. A number of other volcanoes in Alaska have summit craters with variable amounts of acidic, geothermal water that has the potential for slow leakage or sudden release with similar results. High mercury concentrations in these waters are another potential source of damage to biota around volcanoes with active hydrothermal systems. However, little systematic work has been done to map the occurrence of mercury and other toxic elements around volcanoes in Alaska, so it is not possible to say how widespread a threat this could be.

Modern Fisheries Community Vulnerability

Figure 2 shows locations of fishery dependent communities with respect to the historically active volcanoes (those most likely to erupt). Many communities lie within several hundred kilometers of volcanoes and thus are at high risk of ash fall and interruptions of transportation and other services in the event of even small or moderate eruptions. Prevailing winds for volcanic areas along the Aleutians will carry most airborne ash generally eastward and then southeast over the Alaska panhandle.

Of the 136 fishery-dependent communities in Alaska, 7 are located within 30 km of historically active volcanoes (Figure 2). For illustration purposes, we chose 30 km as the outer limit of most significant impact of tephra (ash)-fall events (Blong 1996). Ash-fall thickness for a single eruption pulse usually decays exponentially from source, and concentric circles ignore the impacts of prevailing winds, which tend to produce elongate zones of ash fall. The community of Dutch

Harbor/Unalaska, which ranks nationally as one of the top three ports for quantity and value of commercial fishery landings, is one of the communities located within 30 km of an active volcano. Other communities within 30 km of volcanoes include Atka, Akutan, King Cove, False Pass, Perryville, and Port Heiden. Moreover, even minor ash clouds and ash fall events can completely paralyze transportation, particularly aircraft, which are critical to remote Alaskan communities and any industry that relies on rapid delivery of perishable product. For example, a news release from Alaska Airlines, released on 19 May 2007, indicated that the airline transported more than 350,000 kg of fresh Copper River Chinook salmon *Oncorhynchus tshawytscha* on the first day of the fishing season and predicted that more than 2 million kg of these fish would be transported during the entire Copper River fishing season between May and July. Popular fisheries with product recognition, such as the Copper River Chinook and sockeye salmon *O. nerka* fishery, rely on air cargo to deliver product quickly to markets in the continental United States. Because Anchorage International Airport serves as a hub for nearly all air traffic in and out of Alaska and within the state, any impact to that airport can affect air traffic from communities not directly impacted by eruptions. The duration of these impacts vary with intensity and location of event. Following the 1992 eruption of Mount Spurr, Anchorage International Airport was closed for 20 h and more than 100 domestic and international flights in and out of Alaska were cancelled (Casadevall and Krohn 1995). Ash and coarser particles can also clog waterways or produce floating rafts of pumice and debris, potentially impeding ship traffic, another key aspect of the fisheries infrastructure. Marine vessel traffic can also be affected by the primary process of ash fall, which can interfere with engine operation and radio and navigational instrumentation.

Earthquake Hazards and Fisheries

Seismic hazard maps, indicating the expected intensity of earthquake ground motion, indicate that all of the southern Alaska margin and much of central interior Alaska is susceptible to earthquakes (Figure 3) and all fishery dependent communities in Alaska are at some risk of seismic activity (Figure 4). Large earthquakes (magnitude 7+) in southeastern Alaska are related to the Queen Charlotte–Fairweather transform fault. This fault is essentially a northern continuation of the famed San Andreas Fault, which caused the 1906 San Francisco earthquake. This fault is nearly vertical and allows the Pacific Plate to move north-northwestward relative to the North American Plate. This fault has produced earthquakes up to magnitude (M) 7.8. The Pacific Plate is being subducted beneath the southern Alaska margin, and earthquakes are generated along the entire plate interface. Earthquakes generated along the shallow part of the plate interface are referred to as megathrust earthquakes. Worldwide, megathrust earthquakes cause the largest earthquakes, with magnitudes of 8–9+. Down dip of megathrust earthquakes are those generated by bending of the subducting slab. These so-called "Benioff zone" earthquakes are commonly less than magnitude 5, occasionally venture into the magnitude 6 range, and might reach lower magnitude 7. The M6.8 Nisqually earthquake that occurred in 2001 in Washington was such an earthquake. Earthquakes less than magnitude 6 rarely cause damage to modern facilities, rarely cause secondary effects such as landslides, and do not have surface rupture. Thus, it is earthquakes larger than magnitude 6 that we are most commonly concerned with for an understanding of earthquake hazards, and moreover, it is usually earthquakes greater than magnitude 7 that have substantial human impact. In the case of southern Alaska, these are almost exclusively megathrust earthquakes.

Virtually all damaging earthquakes are caused by the sudden movement of rock along a fault. Earthquake magnitude is proportional to the area that slips (the rupture area) during an earthquake. Megathrust earthquakes are generally less than 30 km beneath the Earth's surface, and Benioff zone earthquakes are from roughly 30 to 150 km deep. Thus, it is important to note that the rupture area for earthquakes of magnitude 6 or less is relatively small when viewed from 10 or more kilometers

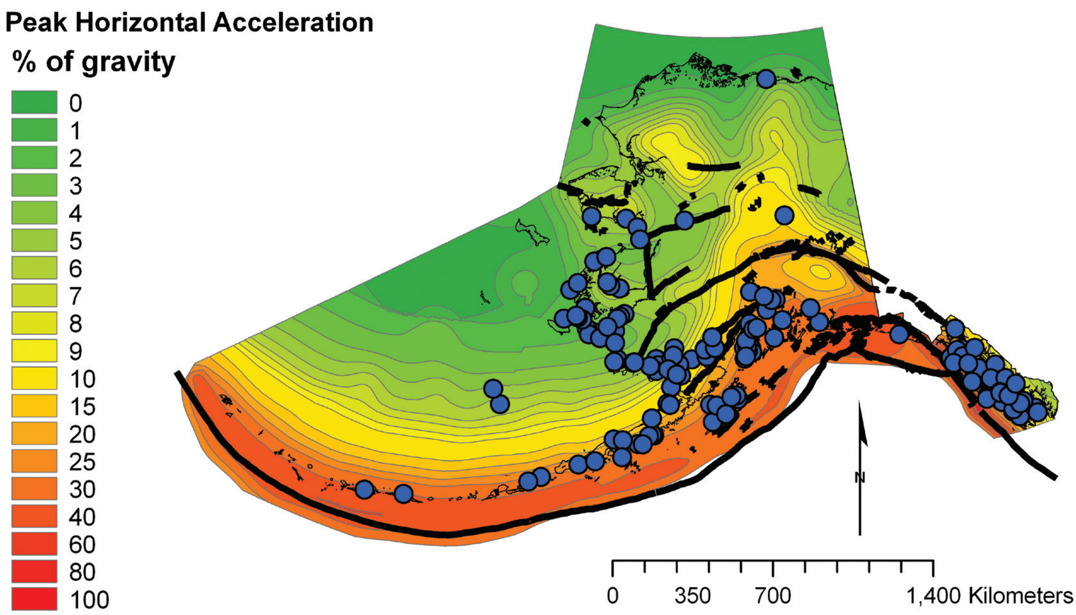

Figure 3. Distribution of fishery dependent communities (gray circles) relative to seismic risk (10% probability of exceedance in 50 years), peak horizontal acceleration in percentage of gravity and major faults of Alaska (black lines).

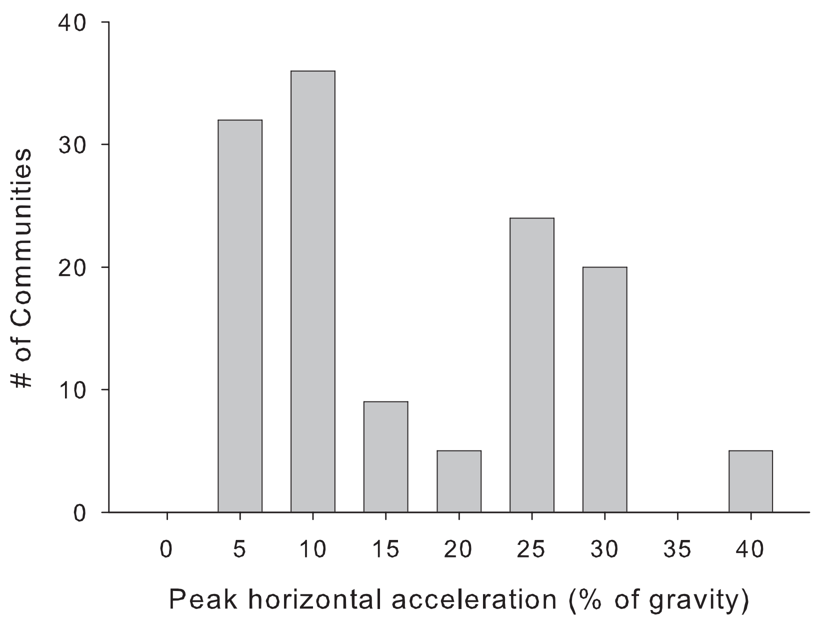

Figure 4. Number of fishery dependent communities relative to expected earthquake ground motion expressed as peak horizontal acceleration in percentage of gravity (10% probability of exceedance in 50 years). Greater peak acceleration indicates greater intensity of ground movement.

away. Conversely, it is a very large area that slips in an earthquake of magnitude 8 or larger. And it takes time for the rupture to move over the entire area that slips. Earthquakes typically rupture at a velocity of 3 km/s; thus, if a rupture proceeded from one end to the other of a 300-km-long fault, it would take about 100 s to rupture. Often people wonder, "where was the epicenter of the earthquake?". The epicenter is the location on the earth's surface where the earthquake initiated, but a more important feature to understand about larger earthquakes is what area slipped in the earthquake—this will more fully inform where the direct effects of the earthquake are likely to be found.

Earthquake effects are caused by earthquake magnitude, the distance from the fault that ruptured, the direction of fault rupture, the duration of ground shaking, and the type of ground one is located on. Small earthquakes do not cause problems; nor do distant large earthquakes if they are far enough away. Some locations will experience greater effects if the fault rupture is toward the locality. Some types of soil (that is, the sediment above bedrock) are more susceptible to high ground shaking and failure than others. In general, poorly consolidated, wet, sandy sediments are the most likely to produce high ground accelerations and to fail in an earthquake. Failure can take the form of rockfall, sediment flows, or landslides—either above sea level or beneath the ocean's surface. Moreover, the larger the earthquake, and the longer the duration of fault rupture, the longer the duration of shaking and the more likely for it to have effects.

Ground shaking can damage buildings and facilities if they are not designed to withstand the conditions encountered in an earthquake. Moreover, nonstructural hazards also cause damage and kill people. Nonstructural hazards refer to anything inside a building that can cause damage, such as falling bookshelves, mirrors, shelving, and ceiling fixtures. Improperly secured nonstructural hazards are one of the greatest risks for people living in earthquake country.

In addition to damage caused by earthquake shaking, much damage is caused by secondary hazards. Secondary hazards include landslides, as mentioned above, but also fires and tsunamis. Most damage from the 1906 San Francisco earthquake was related to fires, so it presents a threat that should not be ignored in other earthquakes. Tsunamis are a significant hazard—particularly for fishing communities, which are situated along the coasts. Tsunamis are formed by two mechanisms, and some earthquakes cause both kinds of tsunamis. Tectonic tsunamis are typically generated by slip along the megathrust or splay faults. The upward motion of the Earth's crust over part of the rupture area generates a wave that can travel thousands of kilometers across oceans. The 2004 Indian Ocean earthquake is an excellent recent example. There is often 20 min or more between the time of the earthquake and the arrival of these tsunami waves, and thus, tsunami warning systems can be effective in preventing the loss of life and property. Tsunami warning systems are designed to issue watches and warnings within about 5 min of a large (M7+) offshore earthquake. Submarine landslides also generate tsunamis. These tsunamis typically occur above the rupture area of the causative earthquake and inundate the shoreline within a few minutes of the earthquake. Tsunami warning systems are not effective for this kind of tsunami hazard. Rather, risk mitigation for these tsunamis centers on developing inundation maps, which can be used to advise local evacuation routes, development, and earthquake response.

Most of these factors affect the ability to process and ship fish, and we leave it to the reader to imagine the ways that earthquakes and tsunamis can damage harbors, runways, fish processing plants, communities, electrical supplies, refrigeration systems, and human life.

Earthquake Effects on Fish and Fish Habitat

Earthquake waves likely have minimal impact on adult fish at a large scale. Earthquakes produce waves that can travel through the Earth and at its surface. Surface waves do not travel through water. There are two types of earthquake body waves—P, or compressional, waves and S, or shear, waves. S waves do not travel through liquids and thus would not be a factor. There may be some percussive effects of the P waves on fish in the region above the rupture area, but scuba divers have experienced earthquakes underwater without ill effect. Divers in Hawaii experienced a M6.7 earthquake, and a subsequent 6.0 aftershock, at a depth of 75–80 ft and described the experience as follows. "We heard this sound, like giant pistons, louder and louder and louder. Vibrations hitting you from all around and they just keep getting louder and more intense and in the water, you don't know where sound is coming from. There is just this stunningly high volume and pressure. It felt like I had a plunger on each ear and someone was pulling and pushing out. There was a shaking in my chest like someone pounding on it" (Polancy 2006). Although this experience was terrifying, the divers suffered no subsequent physical distress. The divers also noted that as the sound of the earthquake increased, schools of fish dove for reefs and down into the coral.

The exception might be if the earthquake occurred at a time that fish were particularly sensitive to their effects. For example, during incubation, eggs and embryos of salmonids are susceptible to mortality induced by mechanical shock or movement (Smirnov 1954; Jensen and Alderdice 1989; Jensen 1997). It is assumed that mortality associated with mechanical shock could occur in naturally spawned redds by activities such as pile driving, blasting, road construction, or seismic activity (Jensen 1997), but evidence of such mortality is scarce. Following a magnitude 9.2 earthquake, Noerenberg and Ossiander (1964) reported increased mortality in pink salmon *O. gorbuscha* alevins, resulting, in part, from mechanical shaking and shifting of stream gravel. In this case, mortality was not associated with sensitivity to mechanical shock, but rather due to the crushing and grinding action of the substrate.

Submarine landslides are likely to be the most significant cause of fish mortality and habitat disruption. Submarine landslides are commonly triggered by earthquakes, but not always. In 1994, a submarine slide in Skagway, Alaska was likely triggered by a combination of an extreme low tide and construction equipment and materials placed on the slide block. The fjords and glacial landscape of coastal Alaska are an ideal geologic environment for producing submarine landslides because they deposit sediment on the steep walls of fjords, which can subsequently fail. Much of the southern Alaska margin is located above the megathrust and Benioff zone, and thus, there are numerous earthquakes to act as triggers for submarine landsliding. Submarine landslide masses can travel great distances and may cause a restructuring of the bottom of fjords, resulting in bottom fish mortality and disturbance of their habitat.

The 1964 Earthquake as an Example of Effects on Fisheries

The 1964 M9.2 earthquake in southern Alaska is the second or third largest earthquake ever recorded, the largest historical earthquake in North America, and the first well-documented megathrust earthquake (Plafker et al. 1969). It represents a near worse-case scenario for considering impacts of an earthquake on fish and fisheries and displays nearly all possible earthquake effects. The earthquake severely impacted numerous coastal communities, including Kodiak, Port Lyons, Homer, Seward, Kenai, Anchorage, Whittier, Chenega, Valdez, and Cordova. Harbor facilities were substantially damaged or destroyed at Kodiak, Homer, Seward, Whittier, Valdez, and Cordova. This damage was accomplished in part by shaking at all the communities and also by uplift at Cordova, by the tectonic tsunami at Kodiak and Seward, and by the submarine-landslide generated tsunamis at Seward, Whittier, Chenega, and Valdez. Airports were still operational after the 1964 earthquake. However, modern runways are longer than those in use in 1964, and the Anchorage International Airport lies above soils with a significant likelihood for ground failure, so earthquake planning scenarios should include the possibility of how to deal with the temporary loss of use of the Anchorage International Airport. The effects on communities were detailed in a series of USGS reports (Professional Papers 542A through G), and although fish processing plants or fishery specific transportation networks were not specifically studied, it is clear that fish processing plants, and the ability to transport fish products, were severely impacted. Today, there is a greater emphasis on cold storage and more transportation of fish products by air. Thus, it is important to recognize that if, for example, the Anchorage airport was closed due to earthquake damage, it would affect fisheries thousands of miles to the west, which commonly ship product through the airport.

Fish habitat was affected in the 1964 earthquake mostly through uplift and submarine landslides. The southern part of Prince William Sound was uplifted up to 9 m. This would have the greatest effect on anadromous fish in this region. There were some direct negative impacts on pink salmon alevins due to shaking and movement of the streambed (Noerenberg and Ossiander 1964), but within the areas of uplift, new spawning areas were created, and it has been suggested that the potential productivity of pink salmon may have increased (Noerenberg and Ossiander 1964; Hillborn and Eggers 2001). In the northern portion of Prince William Sound, subsidence was up to 2 m, but it was more commonly 1 m or less where there were salmon streams. Subsidence may have eliminated some spawning areas close to the ocean and perhaps caused a few fish to look for areas further upstream.

Submarine landslides caused by the 1964 earthquake affected bottom fish and fish habitat. Changes to the ocean floor are best documented in northern Resurrection Bay, near Seward, and in Port Valdez, near Valdez. In Resurrection Bay, more than six landslides formed around the northern part of the bay, coalesced at the sea floor in the middle of the bay, scoured sediment from the bottom, and deposited the reworked material in a deep region from 6 to 13 km from the source (Haeussler et al. 2007). The deposit covers more than 15 km^2 and is typically more than 3 m thick. A similar circumstance affected Port Valdez (Lee et al. 2006, 2007). There was a single large submarine landslide, which started at the east at the fjord-head delta, with a volume between about 0.4 and 1.0 km^3. The slide covered about three-fourths of the length of the fjord (Lee et al. 2006, 2007). Landslides from another source covered the remainder of the fjord bottom. In all, more than 90 km^2 of the ocean bottom was resurfaced by these landslides in Port Valdez.

Thousands of fish were killed by the slides in Port Valdez. At the time of the earthquake, two men were logging in Valdez Narrows, which is the entrance to Port Valdez (Plafker et al. 1969; D. Ferriens, commercial fisherman, personal communication). They experienced the earthquake and observed the subsequent tsunami waves traveling southward out of Port Valdez and into the Narrows. Two and a half hours after the earthquake, and near nightfall, they headed back into Port Valdez in their boat. They saw large numbers of exceptionally large dead rockfish floating at the water's surface with their distended stomachs protruding out their mouths. As the fish normally inhabit deep water, and are sensitive to rapid pressure changes, as commonly seen during hook and line fishing, Plafker et al. (1969) inferred that the fish "probably were killed when they were forced up off the bottom by turbulence related to the inferred submarine slides." Although these were the only fish observed to be killed at the time of the earthquake, it is notable that other fish species are not likely to float to surface if killed in a similar manner. Thus, although it cannot be proved, it is likely that there were additional fish casualties.

Discussion

Natural hazards, such as volcanoes and earthquakes, create risks to communities throughout Alaska. For fishery dependent communities, it is important to understand the nature and distribution of these hazards in order to prepare for future events and limit impacts of those events. Warning systems for volcanoes and tsunamis can help to mitigate loss of property and life. However, communities and businesses need to understand the nature of the warnings (such as does the warning mean I need to be merely alert to the hazard? Or does it mean that the hazard is imminent?), and the economic consequences of improperly timed, or even wrong, warnings, can be catastrophic, even leading to ignored warnings or lack of support for monitoring efforts.

We suggest that on the whole, volcanoes are more likely to affect fish in rivers, streams, and lakes, whereas earthquakes are more likely to affect fish on the ocean bottom. Volcanic eruptions can have devastating effects on individual drainages, whereas submarine landslide-generated tsunamis can affect broad areas of the ocean floor—particularly in fjords. Given the long evolutionary history of fish on Earth, they have evolved to accommodate these hazards, but the combination of a natural hazard event with overfishing may lead to the overall decline in a fish population.

Little systematic research has been conducted concerning the geologically short-term impacts of volcanism and earthquakes on fish and fish habitats, with some notable exceptions, such as the research described by Bisson et al. (2005) following the 1980 eruption of Mount St. Helens in Washington. Bisson et al. (2005) found that recovery could be quite rapid with periods of high food resource productivity in the first two decades following the eruption leading to rapid recovery of fish. Bisson et al. (2005) also warned that management activities or introduced species can have significant impacts on the recovery of native fishes. Research into the effects of seismic waves on fish eggs, embryos, and redds would be relatively simple to accomplish. Research into various aspects of changes in water chemistry caused by volcanic outbursts could also be accomplished. Alaska provides a unique opportunity to begin gathering baseline data to evaluate the role of earthquakes and volcanoes on the distribution and ecology of fishes.

Plate tectonics has existed on Earth certainly for the last 2,500 million years and likely longer. Fish have evolved and thrived for about the last 425 million years. Thus, in the long view, fish have thrived in part because of plate tectonics and despite the hazards intrinsic with plate movement. Fishes found in Alaskan waters have evolved traits and behaviors that have allowed their continued existence in spite of these risks, such as the ability to rapidly colonize and explore new streams for spawning (Mecklenburg et al. 2002). As a result, the structure and distribution of fish populations have been significantly shaped by natural hazards in Alaska.

Humans and communities are subject to these same hazards and need to respond through planning and preparation to minimize the potential impacts of these natural events to the infrastructure used to harvest and distribute fishery resources. Clearly, for all hazards, it is best to build in a location where the risk is minimized. Given that all locations have some exposure to earthquake hazards, building homes and facilities to modern building codes is an excellent first step to minimizing losses in future earthquakes. Building codes, however, only specify minimum standards for safe construction and some additional design effort could result in structures that are usable after a large earthquake, not just one that does not kill people. Preparation for earthquakes should also include assessment of nonstructural hazards within buildings and secure furniture and equipment that is susceptible to falling. Last, people need plans on what to do if an earthquake or volcanic event should strike. Evaluating the potential impact scenarios requires an understanding of the distribution of risks, the potential impacts, and how impacts are created. Emergency planners suggest that consideration of various scenarios helps development of effective plans and facilities.

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